The Effect of Non-Orthogonal Forms on Energy Consumption in Tall Office BuildIngs

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Abstract

This paper focuses on the relation between the building form and energy performance in tall office buildings. It deals with one common generic architectural form of contemporary designs and its derivations. The LT (Light and Thermal) method, developed in UK, was used to estimate expected energy consumption after adjusting its assumptions to suit Khartoum's climatic conditions and non-orthogonal forms. The findings of this study can be quite useful for architects at early stages of the design process (sketch and preliminary design) when no detailed information is available yet for advanced simulation and energy performance assessment techniques. The findings compare calculated energy consumption of five selected forms: box, twisted box, tapered box, bent box and tapered twisted box. The conclusions suggest that up to one-third of the variations in energy consumption could be attributed to changes in basic forms at early design stages. Self-shading forms with controlled glazing ratio perform noticeably better than other forms.

Keywords: Architectural form, energy consumption, Khartoum, office buildings, initial design stages.

مستخلص

تركزهذه الورقة على العلاقة بين شكل المبنى الخارجي واستهلاك الطاقة في المباني المكتبية العالية. تتناول الدراسة بعض الأشكال النمطية للعمارة المعاصرة ومشتقاتها. تم استخدام طريقة الضوء والحرارة (LT method) المطورة في بريطانيا بعد مراجعة وتعديل افتراضاتها لتناسب مناخ منطقة الخرطوم والأشكال غير المتعامدة. نتائج البحث يمكن أن تكون مفيدة للمعماريين في المراحل الأولية لعملية التصميم (الفكرة الأولية) حيث لا يكون التصميم مفصلا بصورة كافية تتناسب والكثير من برمجيات المحاكاة وتحليل استهلاك الطاقة. النتائج تقارن استهلاك الطاقة في خمسة أنواع من الأشكال: المكعب، المكعب الملفوف، المكعب المدبب، المكعب المحني والمكعب المدبب الملفوف. توضح النتائج أن التغيير في شكل المبنى الأساسي له تأثير كبير في صرف الطاقة (حوالي الثلث). الأشكال التي تظلل نفسها مع التحكم في نسبة الأسطح الزجاجية حققت مستويات أقل في صرف الطاقة.

الكلمات المفتاحية: الشكل المعماري، استهلاك الطاقة، الخرطوم، المباني المكتبية، مراحل التصميم الأولية.

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Introduction

The design process of contemporary tall office buildings is complex and is getting more so with the emergence of new issues of sustainability and energy efficiency.Decisions like building form, orientation and façade design have major impacts on the building's energy performance [1]. Hence, the sustainable energy efficient integrated design process has to start as early as schematic design phase [2]. Moreover, the evaluation and feedback on selected forms is needed to improve the overall energy performance of the building. This cyclic process, which is represented in fig.1, requires a quick and simple technique to help the designer in studying the potential of different building forms.

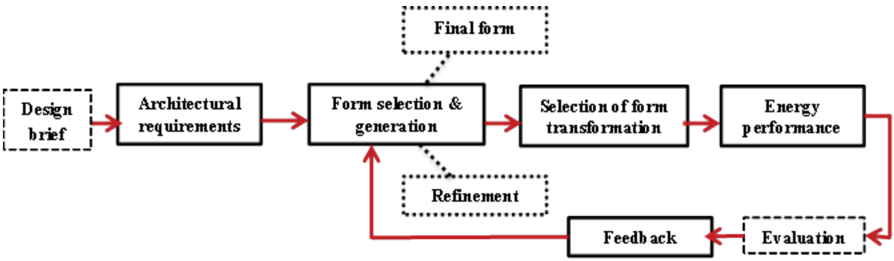


Fig.1: Schematic design phase of a tall office building

Feedback on energy evaluation performance in building encouraged the use of energy tools in the design process [3]. Energy tools are categorized to include energy simulation tools and energy design tools. According to Pedrini, the second category is 'more purpose specific'[3]. Amongst the design tools Light and Thermal (LT) Method, developed by Baker and Steemers, is one of techniques that gives quick results with few inputs that are usually available in the early design stages[4]. However, the use of LT method is limited to the climates of Europe and to the regular geometrical forms of non- domestic buildings[4]. The adjustment of clear sky conditions, correction factors and climatic consideration in addition to the non-orthogonal angles in LT method, will generate new LT curves matching the climate of Khartoum and the characteristic of non-orthogonal form derived from box shape.

Vollers categorizes "box" as one of the basic shapes which are commonly used in office buildings[5]. His study classifies the shapes of contemporary non-orthogonal tall buildings under four basic categories and number of sub categories. The study of energy consumption in different forms is important to evaluate the various options of forms in the early stages of office building design. Taking box shape as one of the common form options, and evaluating it and its transformation will guide the designer to select the best fit transformation options according to the plans of energy saving.

2.Problem statement

With advances in Computer Aided Design(CAD) and 3D modelling software, non-orthogonal tall buildings forms are emerging with an increasing degree of geometrical variations and complexity [5]. Furthermore, form refinement after evaluating expected energy performance may provide a quick and heuristic approach to achieving energy efficiency.

As described by Laseau (fig.2); energy is classified under the information of form in the design variables [6].The studies which try to classify and simplify the non-orthogonal forms of tall buildings set minimizing energy consumption as the main aim of categorizing complex forms transformations. For example, the study of Vollers contended that forms categorization technique enables analysis of sustainable performance of distinctive tall building shapes [5]. This emphasizes that architects are looking for quick and practical guidelines to compare the performance of building form options, especially in cases of tall complex buildings.

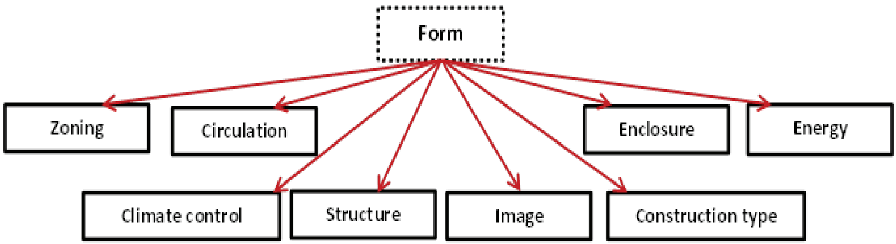


Fig.2: Information of form as proposed by Laseau (2000)

Climate control is also important in optimizing the building layout, zoning, form and energy performance. Evaluating form performance according to climate is a common approach among researchers. For example Cho (2004) proposed a hypothetical building model to assist architects in determining the overall building form in respect to regional climate at the early stage of the design process [7]. The study of Cho concentrated on office buildings as a type of buildings that requires cautious energy analysis. His study is based on evaluating the performance of different building forms considering climatic factors and architectural requirements.

3.The objectives of the study

The study aims to evaluate the energy performance of box-shaped building form and its non-orthogonal transformation in order to set rules of thumb in total energy consumption and guide architects to select the optimum transformation. This selection is based on the little information available in the sketch and preliminary design stage of office building project which are: sketched floors layout, floors areas, number of floors, floor to floor height and window to wall ratio in addition to the rules of occupied floor area, hours of operation and activities carried out in the building spaces.This information could be fixed in the brief design of office buildings. However, the climatic factor is considered as changeable from location to another. In this study, the climaticconditions of Khartoum are selected as a context to test the energy consumption potentials of box and its transformations.

4.Methodology

To evaluate the energy performance of non-orthogonal forms, a comparative quantitative analysis was carried out to evaluate the form's potentials using an energy tool which corresponds to the climate of a specific site.To perform that, CAD-tool 2.0 morphological scheme of non-orthogonal high-rises was employed as a technique of abstracting and categorizing the complex forms of tall buildings [5]. Although the process of creatingthese forms seems complex, simple categorization of such forms is possible under the same transformation processes which are used to manipulate them (i.e. commands used in creating forms inside software).

The shapes, their transformations and derivations are innumerable;therefore, this study focuses on the "box"as a basic shape in addition to its non-orthogonal manipulations.The study evaluates the "box" as a control/base category in addition to three one-step transforming commands and one two-step transformation.

Under each transforming command several options are tried and evaluated using the LT (Light and Thermal) method. The LT method was introduced by Baker and Steemers (1994) and then developed into manual sheets and excel spreadsheets. The LT Method is an energy evaluation tool which considers building form and façade design in predicting energy consumption[4]. A computer-based model is used to predict annual primary energy consumption per square metre of floor areaas a function of:local climatic conditions, orientation of façade, area and type of glazing, obstructions due to adjacent buildings, occupancy and vacation patterns and lighting levels in addition to internal gains[4].

The LT method is simple and quite easy to use. Both characteristics are paramount to designers during the early development of a building concept, form, building organization and design of façades [3].In this study the climatic conditions were altered in LT models to suit the conditions and context of Khartoum.To match the non-orthogonal nature of the forms under study, the calculations of cooling loads and lighting levels were repeated for different glazing ratios and external surface tilt angles in North, East, South and West façades. The steps of calculation are elaborated as follows:

4.1 Development of energy design tool - advanced modelling of the LT curves

The altered LT curves (fig. 4) are calculated as totals of lighting and cooling loads of the external surfaces of a box-shaped building after dividing it into zones: East, West, South, North and internal zone. The calculations are then repeated at different tilt angles and glazing ratios of the building's surfacesand represented in table 1.The incidence angle of the sun is calculated from the sun-path diagram of 15 degrees north (approximate location of Khartoum).

4.1.1 Lighting

- The daylight analysis is calculated using Ecotect Analysis software. Ecotect Analysis is a 3D building analysis tool that helps designers in simulating
 building thermal and light performance [8].
- The values represent the daylight factors using the sky, external and internal reflected components along with the design sky illuminanation.
- The approximate results are used to determine the need for artificial lighting according to the available amount of daylight and glazing ratio in the façades.

4.1.2 Cooling loads

- Cooling load is calculated according to CLTD (Cooling Load Temperature Differential) method of ASHRAE1997[9].
- The CLTD method is based on dividing the building into zones [9] (fig.3).
- The architectural parameters are chosen to correspond to typical office buildings occupied during the day which are shown in table 2.
- In the advanced calculation of the cooling loads,the tilts of the external surfaces of the building (glazed or unglazed) are taken into consideration in addition to the orientation and different incidence angle of solar rays.
- According to the introduced development of Hee Ko, W., et al. (2012), this concept introduces the effect of sol-air temperature on the tilted opaque surface and the SHGC (Solar Heat Gain Coefficient) and SHGF (Solar Heat Gain Factor) of the glazing materials [10].
- The SHGC value is affected by the incidence angle of the solar rays on surface while the SHGF is affected by the location latitude and orientation of the surface (North, East, South or West).

Table 1 indicates that: in the case of 100% glazing the load varies greatly at different tilt angles.Its maximum value is at 0 degree tilt (horizontal surface). Its minimum value is at 45 degree tilt surface.In the case of 0% glazing the load varies slightly at different tilt angles.Its maximum value is between 45-55 degrees tilt due to increasing effect of indirect solar gain and the effect of sol-temperature.

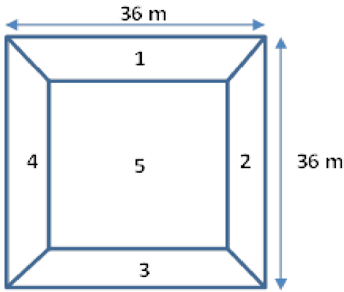


Fig.3: Dividing the model building into zones to perform calculations
1.North 2.East 3.South 4.West 5.Internal zone

Table 1: Total lighting energy and cooling loads in Megawatt/metre square. Year (MW/m.y) in E,W,S and N facades for different glazing and external surface tilt angle

East			glazing ratio			South			glazing ratio		
angle	0	25	50	75	100	**angle**	0	25	50	75	100
90	0.55	0.66	0.77	0.86	0.95	**90**	0.53	0.60	0.67	0.74	0.81
45	0.82	0.67	0.52	0.37	0.22	**45**	0.72	0.57	0.42	0.28	0.13
0	0.44	0.84	1.25	1.66	2.06	**0**	0.44	0.84	1.25	1.66	2.06
-45	0.42	0.57	0.72	0.87	1.02	**-45**	0.40	0.53	0.66	0.79	0.92
West			**glazing ratio**			North		**glazing ratio**			
angle	0	25	50	75	100	**angle**	0	25	50	75	100
90	0.53	0.66	0.80	0.93	1.07	**90**	0.52	0.55	0.58	0.60	0.63
45	0.78	0.63	0.47	0.32	0.17	**45**	0.71	0.55	0.40	0.25	0.1
0	0.44	0.84	1.25	1.66	2.06	**0**	0.44	0.84	1.25	1.66	2.06
-45	0.35	0.44	0.53	0.62	0.70	**-45**	0.35	0.44	0.52	0.61	0.70

Table 1 indicates that: in the case of 100% glazing the load varies greatly at different tilt angles.Its maximum value is at 0 degree tilt (horizontal surface). Its minimum value is at 45 degree tilt surface.In the case of 0% glazing the load varies slightly at different tilt angles.Its maximum value is between 45-55 degrees tilt due to increasing effect of indirect solar gain and the effect of sol-temperature.

4.1.3 The LT Curves - calculations of Khartoum city climate

The total energy consumptions per square metre calculated in table 1are represented in fig.4 below as the LT curves of Khartoum city climate. Fig.4 represents the LT curves of West, East, South and North oriented surfaces in different glazing ratios.
Cosidering the architectural parameters in section 5.1, the generated LT curves were used to read off energy consumption of tested forms in experiments elaborated in section 5.2.

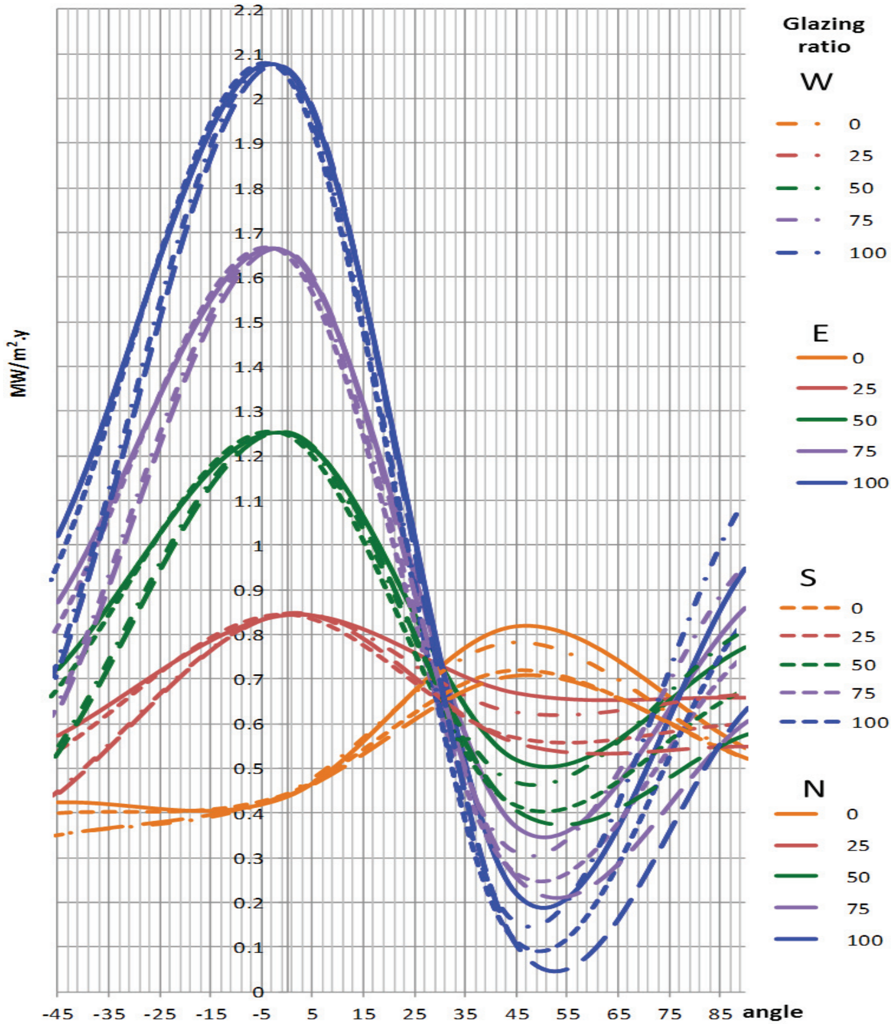


Fig.4: LT curves of West, East, South and North oriented surfaces in different glazing ratios

4.2. Selected site for experimental study

The selected site, highlighted in yellow, is part of Alsunut area (fig.5). The area is planned as the new Khartoum Central Business District (CBD) accommodating tall office buildings of varying heights [11]. The site is used to locate the box form office building (with architectural parameters described in table 2)in addition to the transformed forms which are tested in the experimental study elaborated in section 5.2.

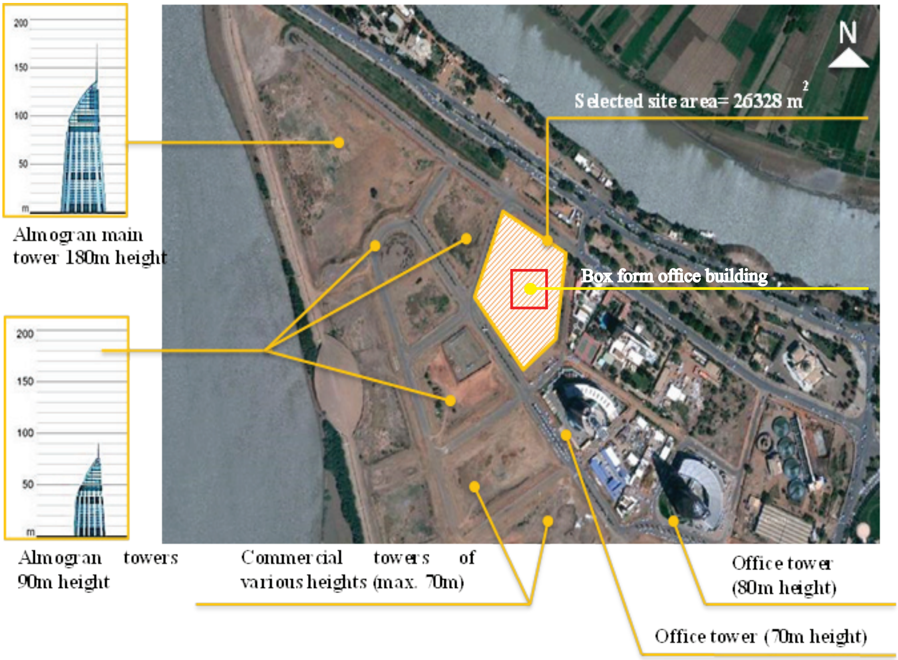


Fig.5: Part of Alsunut project, Khartoum, Sudan - satellite map <www.maps.google.com>
Towers pictures source: reference [11]

5. Experimental study of energy performance in selected form categories

5.1 Architectural parameters

The following design parameters (table 2) are fixed for the studied forms in section 5.2. The assumed values of occupation, working hours and percentage of usable area to core area are made to match the criteria of a typical office building occupied during the day. The obstruction factor (i.e. shading by surrounding buildings) is given a value of 1 for all façades. The fraction of radiant energy that is reflected from ground is also ignored.

Table 2: Summary of architectural parameters values

Factors	Assumptions
Site	Area= 2,600 m² location: (fig.5)
Building gross area	180,000 m²
Building floor area	60m x 60m = 3,600 m²
Number of floors	50 floors
Floor to floor height	4.00 m
Building total height	200 m
Usable area	2,880 m² = 80% of floor area
Occupation	1person per 10 m² (crowded office plan) working from 8:00 to 18:00
Core area	720 m² = 20% of floor area
Ceiling height	3.00 m
Core	Utility center core system
Walls	U-value 0.6 external / 0 for internal walls
Glazing	Single glazed U value= 6
Glazing ratio	Varies (from experiment to another)
Function	Office with open plan
Considered building Forms	Box and transformed box
Obstruction correction factor	1 (for all façades)
Ground reflection factor	1

5.2 Experiments' summary and findings

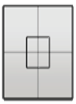
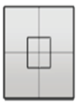
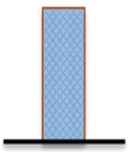
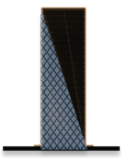
The comparative evaluation was conducted to study the energy consumption in the control form (box) in addition to five selected transformations: twisted box, twisted box+ curvature, bent box, tapered box and tapered twisted box. The annual readings from the developed LT curves (fig.4) are used to fill the

LT worksheets of each tested form. Annual energy consumptions are represented in Megawatt/year (MW/y). Annual energy consumptions per metre square are represented in Megawatt/metre square. year (MW/m2.y). The results of tested transformations are elaborated as follows:

5.2.1. Experiment 1: box and twisted box- glazed façade orientation

The annual energy performances of the box with 100% glazing in N-S façades and boxwith 100% glazing in E-W façades in addition to twisted box with 50% glazing in all façades are summarized in table 3 below. The annual results are represented graphicallyin section 6.1 (fig.6) to compare and discuss the performance of the three tested forms.

Table 3:Annual results of energy use of the box and twisted box obtained from the LT worksheets

Experiment	Category	Top view N	Side view	Glazing ratio	Annual energy consumption (MW/y)	Annual energy consumption per m² (MW/m².y)
1.1	Box (North- South glazed)			0% E-W 100% N-S	100,800	**0.56**
1.2	Box (East-West glazed)			100% E-W 0% N-S	111,600	**0.62**
1.3	Twisted box			50% all facades	97,200	**0.54**

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7.2 Concluding remarks

■ The analysis shows that shading of glazed surfaces is the main factor in reducing solar gain and consequently reducing energy consumption in the tested forms. This highlights the importance of shading glazed surfaces in hot dry climates as the first step towards an energy efficient building.

■ Up to one-third of building energy consumption could be saved if the changes in its basic form are done at early design stages.

■ It is obvious that the number of forms that can be studied is huge; therefore, a software could be developed to give a rough estimate of expected solar gain and/or energy performance.The developed softwares hould have the capability of dealing with basic forms of buildings in addition to commands of creating complex transformations.

8. References

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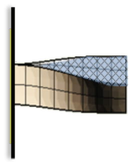
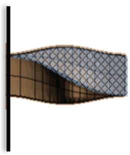
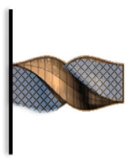
5.2.2. Experiment 2: twisted box + curvature

Experiment 2 included the transformation of the N-S glazed box with 100% glazing ratio in the two façades. The twisting transformation command was carried on in four steps: 45°, 90°, 180° and 360° twisting angle. Each step included reading of annual energy performance shown in table 4 below. As a result of twisting the external surfaces of the box, the glazing ratios vary in the four steps. The results are further discussed in section 6.2.

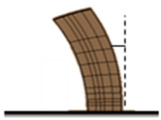
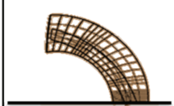
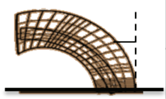
Table 4:Annual results of energy use of twisted box + curvature

Experiment	Category	Top view (N)	Side view	Glazing ratio	Annual energy consumption (MW/y)	Annual energy consumption per m² (MW/m².y)
2.1	45° Twisted box + curvature			30% E-W 70% N-S	106,200	**0.59**
2.2	90° Twisted box + curvature			50% all facades	104,400	**0.58**
2.3	180° Twisted box + curvature			50% all facades	100,800	**0.56**
2.4	360° Twisted box+ curvature			30% E-W 70% N-S	97,200	**0.54**

5.2.3. Experiment 3: bent box

Experiment 3 included the bending transformation of a North façade glazed box with 100% glazing ratio in this façade and 0% glazing in E, W and S façades in addition to the bending transformation of a solid box. The bending transformation command was oriented towards the North façade and carried on in five steps: 15°, 30°, 45°, 60° and 75° bending angle. Each step included reading of annual energy performance shown in table 5 below. The results are further discussed in section 6.3.

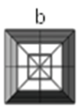
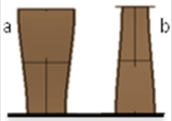
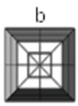
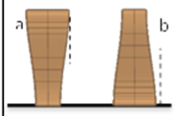
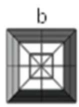
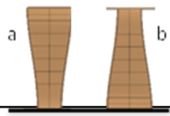
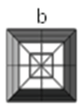
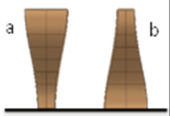
Table 5: Annual results of energy use of the bent box

Experiment	Category	Top view (N)	Side view	Glazing ratio	Annual energy consumption (MW/y)	Annual energy consumption per m^2 ($MW/m^2.y$)
3.1 a	15° Bent box (N-glazed wall)			100% N 0% E, W and S	99,000	**0.55**
3.1 b	15° Bent box (solid walls)			0% all facades	99,000	**0.55**
3.2 a	30° Bent box (N-glazed wall)			100% N 0% E, W and S	99,000	**0.55**
3.2 b	30° Bent box (solid walls)			0% all facades	99,000	**0.55**
3.3 a	45° Bent box (N-glazed wall)			100% N 0% E, W and S	97,200	**0.54**
3.3 b	45° Bent box (solid walls)			0% all facades	100,800	**0.56**
3.4 a	60° Bent box (N-glazed wall)			100% N 0% E, W and S	84,600	**0.47**
3.4 b	60° Bent box (solid walls)			0% all facades	106,200	**0.59**
3.5 a	75° Bent box (N-glazed wall)			100% N 0% E, W and S	75,600	**0.42**
3.5 b	75° Bent box (solid walls)			0% all facades	113,400	**0.63**

5.2.4. Experiment 4: tapered box

Experiment 4 included the upward and downward tapering transformations of the N-S glazed box with 100 % glazing ratio in the two façades and 0% glazing in E-W façades. The tapering transformation commands were carried on in five steps: 15°, 30°, 45°, 60° and 75° tapering angle. Each step included reading of annual energy performance shown in table 6 below. The results are further discussed in section 6.4.

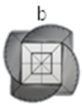
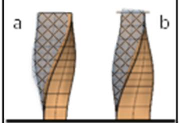
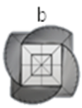
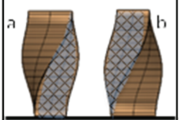
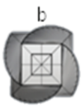
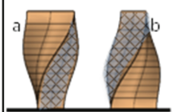
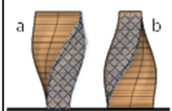
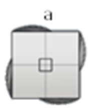
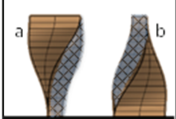
Table 6:Annual results of energy use of the tapered box

Experiment	Category	Top view N	Side view	Glazing ratio	Annual energy consumption (MW/y)	Annual energy consumption per m² (MW/m².y)
4.1 a	15⁰ tapered box (downward)			0% E-W 100% N-S	100,800	**0.56**
4.1 b	15⁰ tapered box (upward)				102,600	**0.57**
4.2 a	30⁰ tapered box (downward)			0% E-W 100% N-S	99,000	**0.55**
4.2.b	30⁰ tapered box (upward)				102,600	**0.57**
4.3 a	45⁰ tapered box (downward)			0% E-W 100% N-S	97,200	**0.54**
4.3 b	45⁰ tapered box (upward)				104,400	**0.58**
4.4 a	60⁰ tapered box (downward)			0% E-W 100% N-S	84,600	**0.47**
4.4 b	60⁰ tapered box (upward)				111,600	**0.62**
4.5 a	75⁰ tapered box (downward)			0% E-W 100% N-S	75,600	**0.42**
4.5 b	75⁰ tapered box (upward)				111,600	**0.68**

5.2.5. Experiment 5: tapered twisted box

Experiment 5 included two steps transformation commands of the N-S glazed box with 100% glazing ratio in the two façades and 0% glazing in E-W façades. These steps are: tapering the box upward or downward in different angles and twisting the tapered box in 90° twisting angle. The tapering transformation commands were carried on in five steps: 15°, 30°, 45°, 60° and 75 ° tapering angle. Each step included reading of annual energy performance shown in table 7 below. The results are further discussed in section 6.5.

Table 7:Annual results of energy use of the tapered twisted box

Experiment	Category	Top view N	Side view	Glazing ratio	Annual energy consumption (MW/y)	Annual energy consumption per m² (MW/m².y)
5.1 a	15° tapered down 90° twisted box			50% all facades	99,000	**0.55**
5.1 b	15° tapered up 90° twisted box				99,000	**0.55**
5.2 a	30° tapered down 90° twisted box			50% all facades	97,200	**0.54**
5.2 b	30° tapered up 90° twisted box				99,000	**0.55**
5.3 a	45° tapered down 90° twisted box			40% N-S 60% E-W	93,600	**0.52**
5.3 b	45° tapered up 90° twisted box				100,800	**0.56**
5.4 a	60° tapered down 90° twisted box			40% N-S 60% E-W	79,200	**0.44**
5.4 b	60° tapered up 90° twisted box				108,000	**0.60**
5.5 a	75° tapered down 90° twisted box			35% N-S 65% E-W	72,000	**0.40**
5.5 b	75° tapered up 90° twisted box				117,000	**0.65**

6.Findings' analysis and discussion

6.1.Glazed façade orientation effect

The results of experiments:

1.1: energy use of N–S glazed box,
1.2: energy use of E-W glazed box and
1.3: energy use of twisted box buildings
are represented in fig.6 below which indicates that:

- The worst result (high energy use) expectedly belongs to the box of full glazed E-W façades and solid surfaces on N-S.
- The solid surfaces on E-W façades + full glaze on N–S façadesbox perform better.
- The best result (low energy use) refers to the twisted box which ensures equal distribution of glazing surface and daylight on all façades.

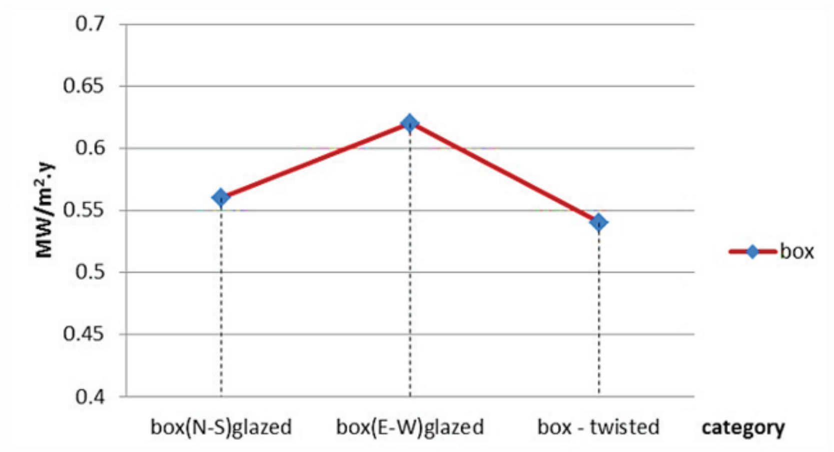


Fig.6: The annual energy use totals of form categories in experiments 1.1, 1.2 and 1.3

6.2 Twist angle effect

The results of experiments:

2.1: 45° twisted box +curvature,
2.2: 90° twisted box +curvature,
2.3: 180° twisted box +curvatureand
2.4:360° twisted box+ curvature

are represented in fig.7 below which indicates that:

- The best result (low energy use) belongs to the box of 360° twisting angle. This could mainly be due to the self-shading effect of the form.
- More divergence in twisting angle results in more rotation of the box surfaces around the twist axis.
- This ensures the distribution of solid and glazed surfaced in all façades.

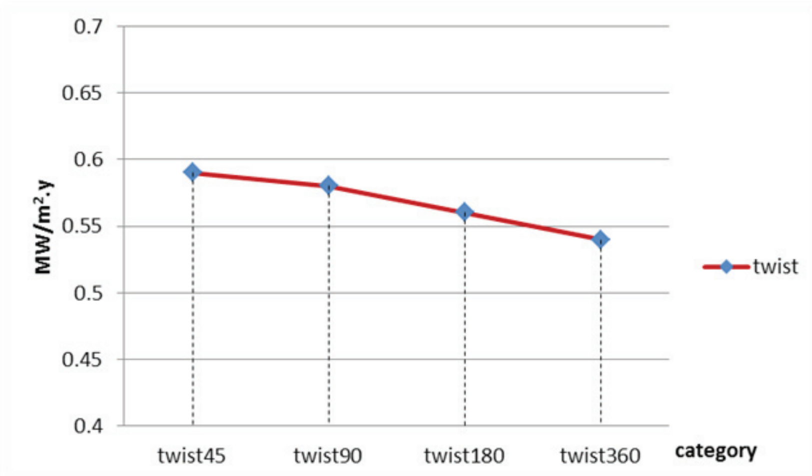


Fig.7: The annual energy use totals of form categories in experiments 2.1, 2.2 and 2.3

6.3 Bend angle effect

The results of experiments:
3.1a:15° bent box(100% N- glazed wall), 3.1b: 15° bent box(solid wall in all façades),
3.2a:30° bent box (100% N- glazed wall), 3.2b: 30° bent box (solid wall in all façades),
3.3a: 45° bent box (100% N- glazed wall), 3.3b:45° bent box (solid wall in all façades),
3.4a: 60° bent box (100% N- glazed wall), 3.4b 60° bent box (solid wall in all façades),
3.5a: 75° bent box (100% N- glazed wall) and 3.5 b:75° bent box (solid wall in all façades)
are represented in fig. 8and 9 below which indicate that:

- Bending the box towards the North, assuming that it is the only glazed façade, decreases the energy use with the increase of bending angle.

■ Bending the box towards the North, assuming that it is a solid façade, increases the energy use with the increase of bending angle.

■ This could be explained by increased shading due to bending in the glazed N elevation case.

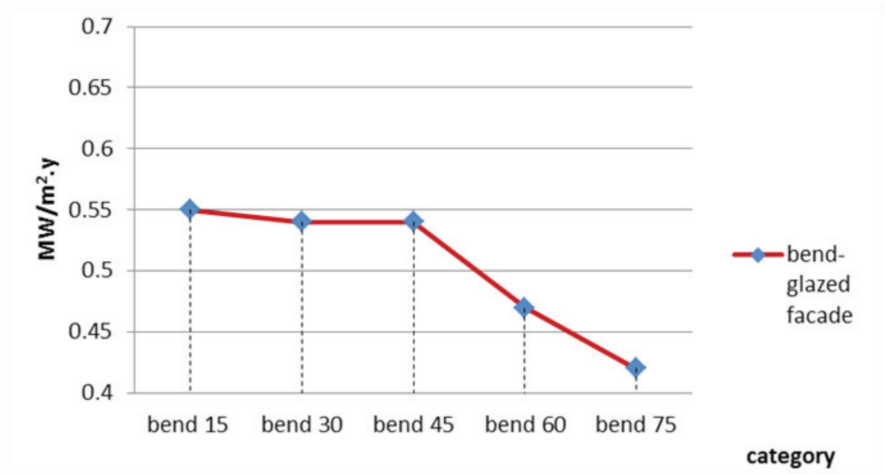


Fig.8: The annual energy use totals of form categories in experiments 3.1a, 3.2a, 3.3a, 3.4a and 3.5a

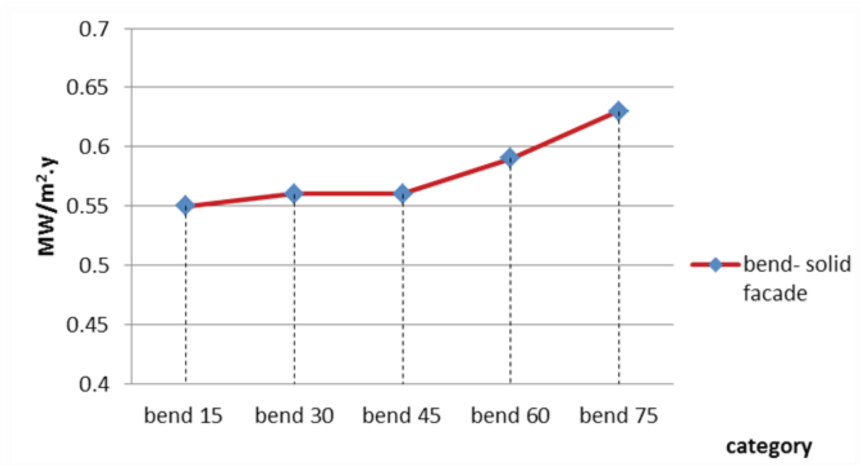


Fig.9: The annual energy use totals of form categories in experiments 3.1b, 3.2b, 3.3b, 3.4b and 3.5b

6.4 Taper angle effect

The results of experiments:

4.1a: 15° tapered box(downward), 4.1b:15° tapered box(upward),
4.2a:30° tapered box(downward), 4.2b: 30° tapered box(upward),
4.3a: 45° tapered box(downward), 4.3b:45° tapered box(upward),
4.4a:60° tapered box(downward),4.4b:60° tapered box(upward),
4.5a:75° tapered box(downward) and4.5b:75° tapered box(upward)
are represented in fig.10and 11 below which indicate that:

- Tapering the box towards an ending point at the top of the building, with glazing in N-Sfaçades, increases the total energy use because of the heat gain through the exposed glass surfaces.
- More divergence in taper angle results in higher energy consumption in building.
- Tapering the box towards an ending point at the bottom of the building, with glazing in N-S façades, decreases the total energy use because this form is self-shading.
- More divergence in taper angle results in lower energy consumption in building.

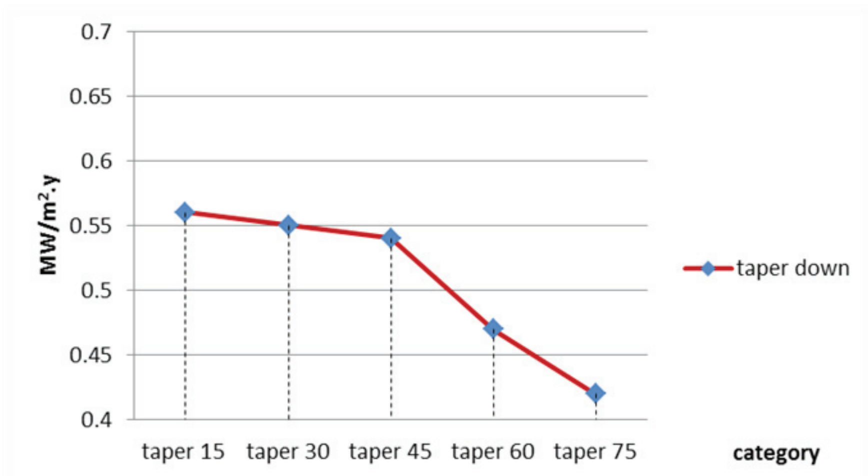


Fig.10: The annual energy use totals of form categories in experiments 4.1a, 4.2a, 4.3a, 4.4a and 4.5a

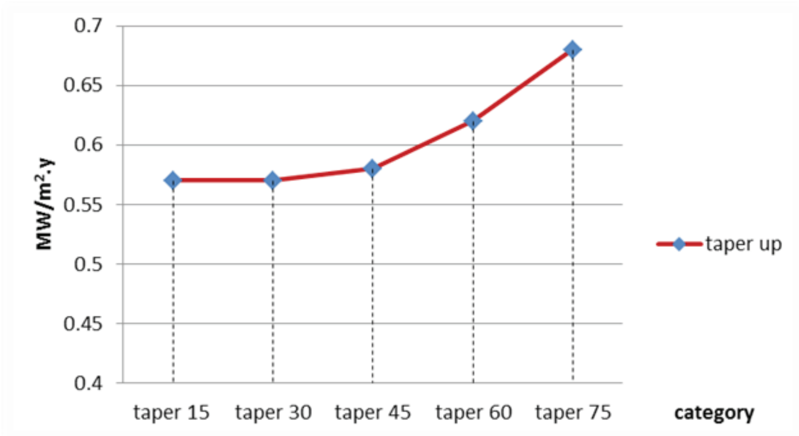


Fig.11: The annual energy use totals of form categories in experiments 4.1b, 4.2b, 4.3b, 4.4b and 4.5b

6.5 Taper and twist angle affect

The results of experiments:

5.1a: 15° tapered down 90° twisted box, 5.1b: 15° tapered up 90° twisted box, 5.2a: 30° tapered down 90° twisted box, 5.2b: 30° tapered up 90° twisted box, 5.3a: 45° tapered down 90° twisted box, 5.3b: 45° tapered up 90° twisted box, 5.4a: 60° tapered down 90° twisted box, 5.4b: 60° tapered up 90° twisted box, 5.5a:75° tapered down 90° twisted box and 5. b: 75° tapered up 90° twisted box are represented in fig.12and 13 below which indicate that:

- The effect of taper angle is the same as in results of section 6.4: taper angle effect.
- At the same time the twist transformation adds more efficiency to the downward tapered box.

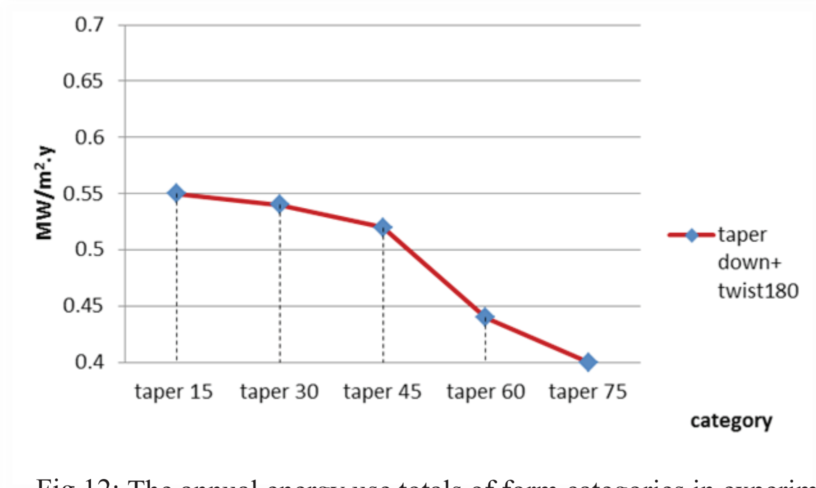


Fig.12: The annual energy use totals of form categories in experiment 5.1a, 5.2a, 5.3a, 5.4a and 5.5a

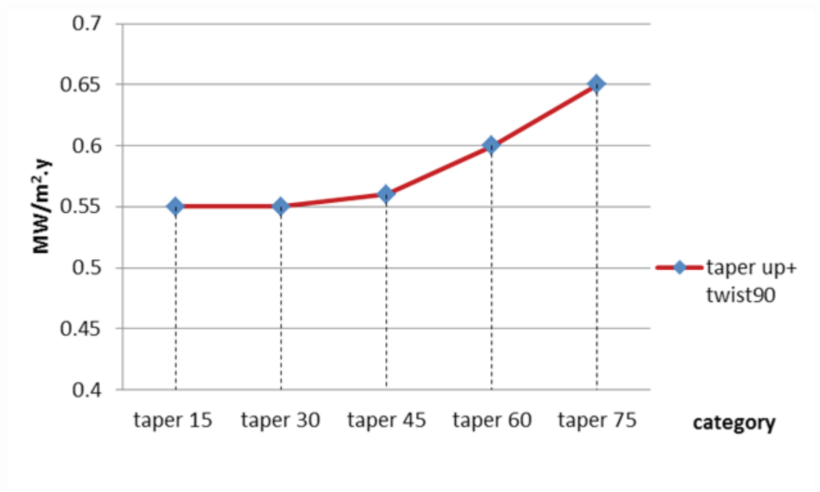
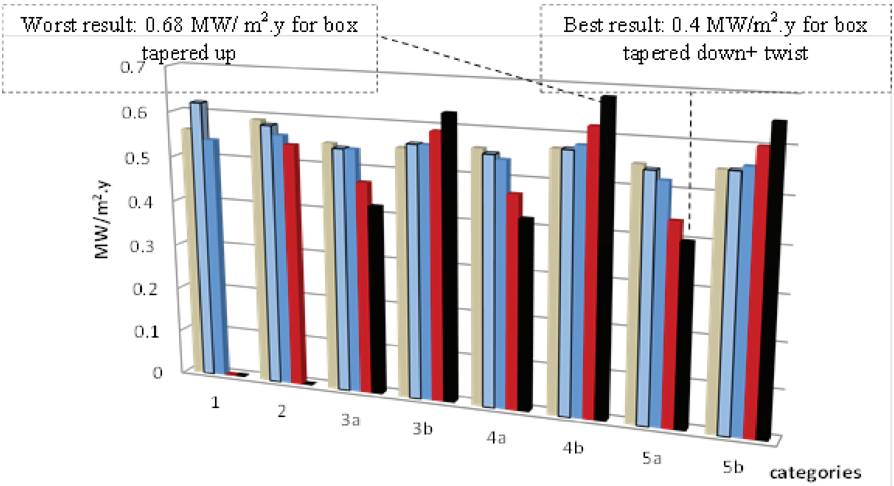


Fig.13: The annual energy use totals of form categories in experiment 5.1b, 5.2b, 5.3b, 5.4b and 5.5b

7. Recommendations and concluding remarks

7.1 Recommendations

The comparison of energy performances of the tested forms discussed in section 6 is represented in fig.14 below which indicates that the self-shading form (tapered down box with 75° tapering angle and 90° twisting angle) saves more than one-third of total energy consumption of the exposed form (tapered up box with 100% glazing in N-S façades and 75° tapering angle).



	1	2	3a	3b	4a	4b	5a	5b
option1	0.56	0.59	0.55	0.55	0.56	0.57	0.55	0.55
option2	0.62	0.58	0.54	0.56	0.55	0.57	0.54	0.55
option3	0.54	0.56	0.54	0.56	0.54	0.58	0.52	0.56
option4		0.54	0.47	0.59	0.47	0.62	0.44	0.6
option5			0.42	0.63	0.42	0.68	0.4	0.65

Fig.14: The annual energy use totals of the tested transformations

Table 8: Key of the tested options within each experiment

experiment	1	2	3a	3b	4a	4b	5a	5b
Option1	N–S glazed box	45° twisted box +curvature	15° bent box (N-glazed wall)	15° bent box (solid walls)	15° tapered box (downward)	15° tapered box (upward)	15° tapered down 90° twisted	15° tapered up 90° twisted
Option 2	E–W glazed box	90° twisted box +curvature	30° bent box (N-glazed wall)	30° bent box (solid walls)	30° tapered box (downward)	30° tapered box (upward)	30° tapered down 90° twisted	30° tapered up 90° twisted
Option 3	twisted box	180° twisted box +curvature	45° bent box (N-glazed wall)	45° bent box (solid walls)	45° tapered box (downward)	45° tapered box (upward)	45° tapered down 90° twisted	45° tapered up 90° twisted
Option 4	-	360° twisted box +curvature	60° bent box (N-glazed wall)	60° bent box (solid walls)	60° tapered box (downward)	60° tapered box (upward)	60° tapered down 90° twisted	60° tapered up 90° twisted
Option 5	-	-	75° bent box (N-glazed wall)	75° bent box solid walls)	75° tapered box (downward)	75° tapered box (upward)	75° tapered down 90° twisted	75° tapered up 90° twisted

Comparing the tested options within each experiment, which are clarified in table 8, it could be concluded that:

- Option 3 in experiment 1(twisting the N-S glazed box)reduces the total solar gain and increases the amount of daylight through distributing the glazing of external surfaces on all façades.
- The twisted surfaces of the box in experiment 2 with smooth curvature maximize shading; thus, they reduce the solar gain of the building.
- Bending the box towards the North (experiment 3a), assuming that it is the only glazed façade, decreases the energy use with the increase of bending angle. That is because bending the box toward the façade maximizes shading of the façade.
- Tapering the box towards an ending point at the bottom of the building, with glazing in N-Sfaçades (experiment 4a) decreases the total energy use because this form is also self-shading.
- The twist transformation adds more efficiency to the performance of downward tapered box as resulted from experiment 5a.